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PULSER FOR THE TEVATRON ELECTRON LENS GUN

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Abstract

To compensate for beam-beam interaction in Tevatron, an “electron lens” is considered to be an effective instrument. When a bunch of electrons with energy in the range (10–16) kV is overlapping with a bunch of antiprotons, the resulting focusing force for antiprotons can be adjusted by changing the electron beam current and by profiling its radial distribution. There exist several scenarios of how the system must function. According to one of them, an electron gun that supplies electrons must be fed by voltage pulses that follow with the frequency of antiproton bunches circulating in the Tevatron, which is about 2.5 MHz. To provide focusing tailored for each individual antiproton bunch, a modulator of the gun (pulser) must allow pulse-to-pulse voltage change.

This report will cover main approaches to a design of a pulser for use with the gun of the Tevatron Electron Lens.

I. TEVATRON ELECTRON LENS

In a charged particle collider, electromagnetic interaction between circulating beams results in a betatron tune shift and tune spread that lead to partial particle loss and reduction of integrated luminosity. In the Tevatron, where the colliding particles are protons and antiprotons, it was suggested to compensate for negative effects of beam-beam interaction by using an “electron lens” only for antiprotons because the intensity of antiproton beam in the Tevatron is much lower than that of proton beam [1].

Fig. 1 shows a scheme of the Tevatron Electron Lens (TEL).

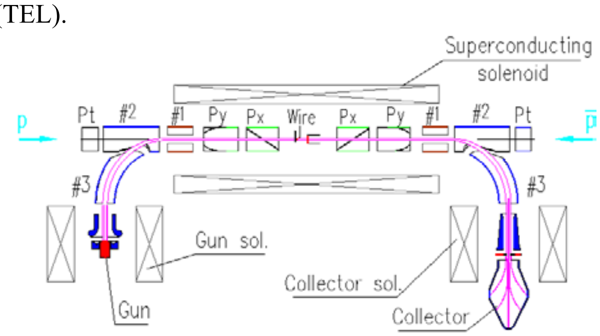

Figure 1. Tevatron Electron Lens

TEL is placed in a straight section of the Tevatron. Electrons are moving from an electron gun to a collector in a strong longitudinal magnetic field in the direction opposite to that of antiprotons. Thus, focusing effect of electron beam in the lens is opposite to that of protons. Length of the lens and intensity of electron beam are chosen to obtain needed focusing strength. To provide linear focusing effect, radial size of electron beam must be larger than that of antiproton bunches. Changing radial profile of electron beam provides an opportunity to compensate for nonlinear focusing effects.

Antiproton beam enters drift space of the lens when it is already filled with electrons. Although proton and antiproton beams are spatially separated in the area where TEL is installed (about 6 mm of separation), to avoid additional orbit distortion, it is not desirable to have electron beam in the drift space when proton bunch comes there. This results is quite strict requirements to the TEL gun modulator as it will be shown below. Proton and antiproton pulse structure in the Tevatron and required timing of electron beam in TEL are shown in Fig. 2.

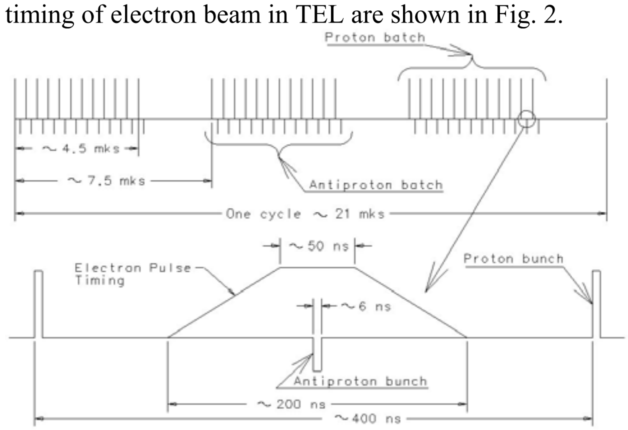

Figure 2. Pulse structure

There are 1113 RF buckets along the Tevatron orbit, but only 72 populated buckets are used to house 36 proton bunches and 36 antiproton bunches. For each sort of particles, populated buckets are arranged in three macro-pulses (or batches) with twelve bunches in each of them. Total length of each macro-pulse is ~4.5 µs. The distance between the batches is ~7.5 µs. The distance between bunches in each batch is ~400 ns.

The length of the drift space is ~2 meters. It takes 33 ns for electrons ($\beta = 0.2$) to fill it. For antiprotons ($\beta = 1$) it takes 6 ns. After the last particle of the antiproton bunch leaves the drift space, it is possible to cut off e-beam. So, taking into the account also the antiproton pulse length, the flat top length requirement to the gun’s extraction voltage pulse is about 50 ns. If to accept with some reserve 200 ns as an ultimate length of the pulse, it leaves 150 ns for the pulse rise and fall time.

To provide reproducible effect, e-beam current must be well controlled; for ideal lens performance, different bunches require different e-beam current settings. The system must work in continuous mode as long as the Tevatron storage cycles last (typically one storage cycles lasts 30 – 50 hours).

Besides the pulses of electron beam to compensate for beam-beam interaction effects, additional pulses are required between the macro-pulses (not shown in the picture) that are used to remove all low energy charged particles trapped in TEL. So totally the system must produce 39 pulses during each period of particle revolution in the Tevatron (~21 μs).

To discuss details of modulator scheme, it is important to understand how the electron gun is designed. As it is shown in Fig. 3, the electron gun consists of a cathode, control electrode (or profiler), and an anode [2, 3].

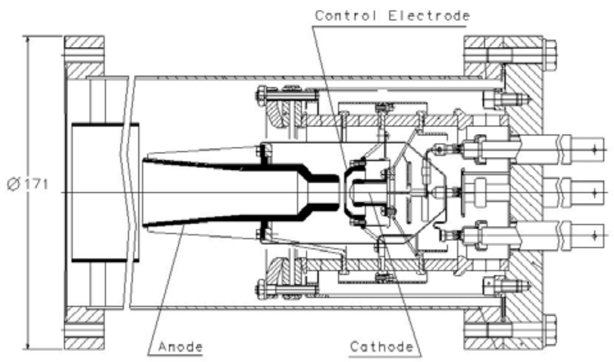

Figure 3. TEL electron gun

The gun generates bunches of electrons with maximal current of ~4A and with quasi-Gaussian current density profile defined by the control electrode. The measured perveance of the gun is 1.8 $\mu A/V^{3/2}$. If operating voltage of 16 kV is chosen, the cathode potential is kept at the level of -16 kV using a DC power supply. The anode potential (also DC) can go up to -20 kV to fully close the gun. The gun is open when the anode potential is brought close to zero by a positive voltage pulse. The gun's electrode capacitances are: ~40 pF anode to ground, ~40 pF anode to control electrode, and ~20 pF anode to cathode.

The gun was successfully tested to meet all design requirements. Its performance as a part of the TEL system was limited though by the existing modulator's maximal voltage (10 kV) and repetition frequency (~ 50 kHz) [4].

The main goal of this study was to understand whether it was possible to build a modulator that does not impose so severe restrictions on the TEL system performance.

II. PULSED POWER SYSTEM

As it was mentioned earlier, for optimal lens performance, different bunches of antiprotons require different e-beam current settings. There are several modes of operation of TEL in discussion, each helping to deal with certain negative effects of beam-beam interaction. The most challenging of them is when independent current setting for each bunch in each batch is used. Depending on priorities of solving antiproton beam dynamics problems, there can be several approaches to a technical solution for the pulsed system of the TEL.

First, it is possible to use a wide band high power amplifier to generate voltage to be applied to the cathode-anode gap of the gun. It is a straightforward way, but not always feasible, as it will be shown later.

Next, it is possible to use a system that employs a pulse-forming network (PFN) matched by a resistive load parallel to the gun's anode-cathode gap. For some modes of TEL operation, this can be an effective solution.

Finally, it is possible to build a linear multi-mode oscillator using only reactive elements (inductances and capacitances, including those in the gun) that generates pulses with shape close to rectangular.

A An Amplifier-Based Modulator

A simplified scheme of an amplifier to use with the gun is shown in Fig. 4.

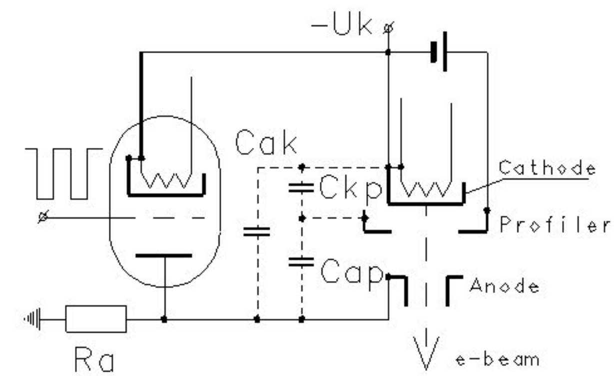

Figure 4. Amplifier-based modulator

When the tube is fully open, its anode potential is close to that of the cathode, and no current is coming out of the gun. If the tube is closed, the anode becomes grounded and e-beam is coming out the gun.

To change the voltage of the gun's anode, one must charge (discharge) capacitances Cak, Cap, and Ckp. With full charging time below 75 ns, the time constant of this circuit must be ~25 ns or less (95% charge level at 3τ). Taking into the account capacitances of connection circuits, the equivalent capacitive load the amplifier $C \approx 150$ pF. This results in the requirement to have $Ra < 160$ Ohm. Then the maximal current through the tube is 100 A (Uk = -16 kV), and maximal power dissipated in the resistor is about 1.6 MW. The average power will be about 0.4 MW. Obviously, the power is too high to allow considering this version of a modulator for controlling each bunch in a batch. Nevertheless, if to allow electrons to be in the TEL drift space when proton bunches pass through it, this option can work. For example, if charging time is 1 μs instead of 75 ns, required anode resistance is 2000 Ohm and maximal power is "only" ~200 kW with average power loss of ~50 kW. Similar amplifier is used at the moment to control only one antiproton bunch from all the three batches.

B. A PFN-Based Modulator

In principle it is possible to use a pulse-forming network (PFN) loaded by a matching resistance to form a voltage pulse of a length needed to charge the gun's electrode capacitances. If to use only one PFN and set the goal to control each pulse individually, it would be necessary to fully charge it during the time gap between the bunches (about 200 ns), which is technically difficult to arrange. It is possible to approach a solution by using several pulse forming lines - one for each antiproton pulse and an additional cleaning one. Each of the PFN-s is charged separately and works only for one (and the same) bunch. In this case charging time is about 7μs. All the PFN-s use the same resistance as a load and they are connected to this load one by one. Connecting each PFN to the load (repetition rate of ~136 kHz) and disconnecting it can be made using an appropriate switch. This design approach is illustrated by a simplified equivalent scheme in Fig. 5.

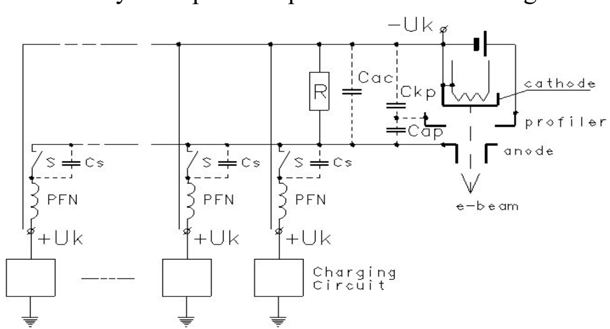

Figure 5. PFN-based modulator

When one of the PFN-s is active, others are separated from the load by open switches that add a capacitive load of (N-1)·Cs to the equivalent gun capacitance C. If to make Cs ≈ 20 pF, this additional capacitance is about 250 pF. It is easy to conclude that the required load in this case R ≈ 62 Ohm. Current in the resistor (and switch) is about 260 A. Maximal power is ~4 MW, and average power dissipated in the load is 720 kW. Although high power is still required to provide needed pulse pattern, each switching device controls only relatively small portion of this power.

In the simplest case, pulse forming circuits can be just storage capacitances, but more complicated circuits can also be used. The system can be significantly simplified if only one or the first and the last bunches in each batch have to be corrected by the lens. Just one storage element can be used charged by a 2.5 μs current pulse with frequency of about 400 kHz. Power dissipated in the load in this case is about 160 kW.

C. Modulator Based on a Multimode Oscillator

Because the TEL gun itself almost does not require active power for operation (only it is required for electron acceleration), it is desirable to have a circuit that can form a quasi-rectangular pulse while not using resistive elements at all. An oscillating network can be activated by connecting to a charged storage element using an appropriate switching device, similar to what is usually done in a simplest voltage-doubling circuit (see Fig. 6).

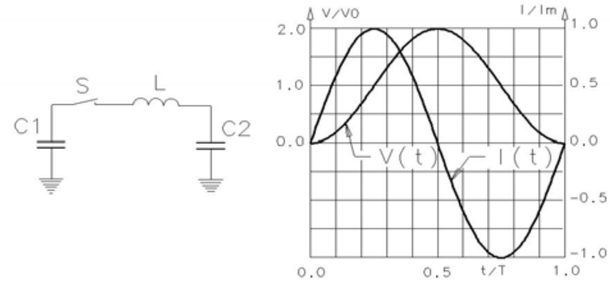

Figure 6. Single-mode oscillator

In this circuit, using a fast switch S, one can initiate oscillations that in one period bring the system in the initial state with zero output voltage and current. This is a convenient moment to interrupt oscillations, add some charge to the storage capacitance C1 to compensate for energy loss, and repeat the cycle at any moment later. Because no resistive elements are used, power dissipation is relatively low: one must only compensate for finite quality factor of the circuit due to dielectric losses and some resistive losses in wires.

This kind of a system can be expanded to generate repeatable trains of pulses of different voltages. For this purpose, a set of independent voltage sources (e.g. charged capacitors) can be used with each source being connected one by one, with needed frequency to an appropriate oscillating network to initiate it. A scheme explaining the work of the system is shown in Fig. 7.

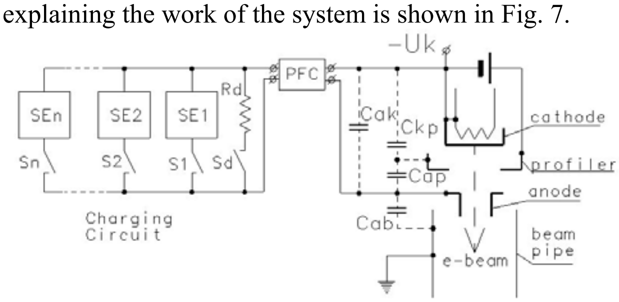

Figure 7. Generation of multiple pulses

An oscillating network is built of three components: storage element SE, pulse-forming circuit PFC, and capacitive and inductive elements that exist in the gun. All the storage elements are identical, but charged to different voltage levels. They can be capacitors or just voltage sources. PFC must be designed to ensure forming reproducible quasi-rectangular pulses in a way that periodically brings the system close to the initial state. The system is activated when it is connected to one of the storage elements. This connection results in appearance of a voltage pulse (presumably of an acceptable shape) applied to the anode-cathode gap (Cak). This voltage controls electron beam current; electron energy is defined by cathode potential because the beam pipe is always connected to the ground. In the end of each oscillation, when current in the switching element is close to zero, the active storage element is disconnected, and the network is ready to be connected to another element, charged to different voltage level.

For the gun perveance of $1.8 \cdot 10^{-6}$, the maximal beam current is about 3.6 A, and with the active pulse width of 100 ns, average power required to support oscillations is about 14 kW. Almost all the power is stored in the beam and in principle most of it can be recuperated. Additional losses in the internal and external elements of the circuit can be of the order of 5 kW (loss tangent of about 0.005 is accepted), so total expected power dissipation is ~ 20 kW (without taking possible recuperation into the account). Configuration of the oscillator-based modulator can vary; equivalent scheme in Fig. 8 presents one of possible solutions.

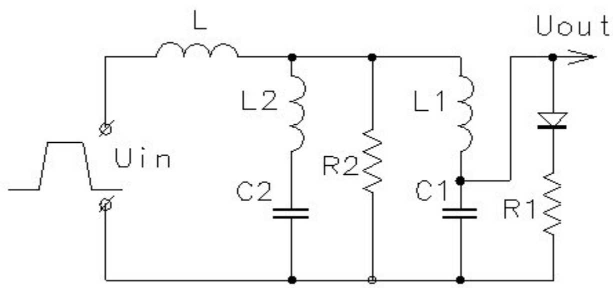

Figure 8. Equivalent scheme of oscillating network

The idea underlying the synthesis of the oscillator is to have the circuit with resonance response at several frequencies. After the circuit is activated, phases and amplitudes of oscillations of partial contours must result in a quasi-rectangular voltage pulse. Capacitor C1 in the scheme represents the gun's anode-cathode gap, element L1 represents inductance of the connecting wires; R1 is a representation of beam load; R2 models power loss in the outer elements of the circuit (dielectric and resistive). Elements L, L2, and C2 are external to the gun (PFC in Fig. 7), and must be chosen. Curves in Fig 9 show input voltage pulse, output voltage pulse, and current charging C1. They were obtained using the next set of parameters: R1 = 4.4 kOhm, R2 = 100 kOhm, L1 = 200 nH, C1 = 150 pF, L2 = 7.5 μH, C2 = 65 pF, L = 4.4 μH.

For simulation purpose, the oscillator in Fig. 8 was excited by a trapezoidal voltage pulses Uin with the length of about one period of oscillations. Frequency of the pulses could be changes arbitrarily. The shapes of the three pulses shown in Fig. 9 differ slightly due to the fact that at the moment when the excitation pulse ends, there is some residual energy in the oscillator. Adding zeroing switch (Sd in Fig. 7) will solve the problem. Within certain range of the circuit parameters, one can get an appropriate pulse shape with the "flat top" length of about 50 ns and with pulsations of about 5 %.

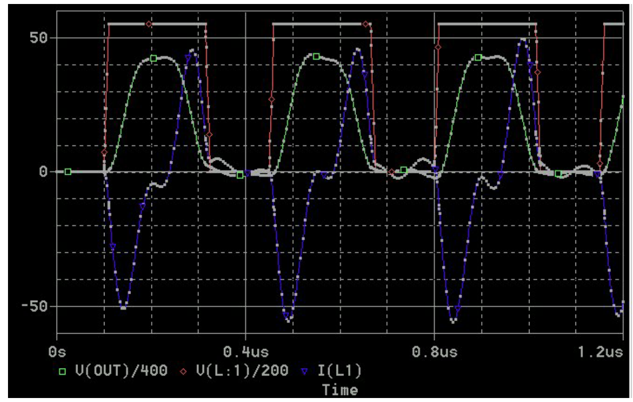

Figure 9. Oscillator simulation results

III. CONCLUSION

Several approaches to the TEL gun modulator have been analyzed. It seems possible to develop an appropriate modulator based on requirements to the TEL system (that are not completely finalized yet). Proper choice of switching devices would be the next step to make. There is no doubt that such a devices can be found (see [5] and [6] for example), but thorough simulation of the system with the switch seems a necessary step before a prototype is built. Range of parameters that provide satisfactory solution for an oscillator-based modulator is quite narrow, and taking into account relatively big power circulating in the system, thermal effects must be properly addressed.

IV. REFERENCES

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